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Bearing Capacity Tests on Ice Reinforced with Geogrid

F. Donald Haynes, Charles M. Collins
and Walter W. Olson

December 1992

Abstract
Laboratory tests were conducted on floating freshwater ice sheets, reinforced with a high-strength polymeric mesh (Geogrid). The mesh was frozen into the ice sheets. Bearing capacity tests were conducted on each ice sheet, whose thickness varied from 3 to 13 cm, while the dynamic loads varied from 1.3 to 23 kN. Comparisons to tests on ice without reinforcement were made; Geogrid reinforcement increased the bearing capacity of thin (49-mm) ice up to 38% and of thicker ice (96 mm) about 10–15%. Failure of the ice with Geogrid reinforcement was local, whereas failure of the ice without Geogrid was over a large area. Displacement of the ice is compared to theory for plates on an elastic foundation. Field tests were conducted at Fort Wainwright, Alaska. A small unit support vehicle (Hagglunds BV 206) was used for loading a reinforced ice sheet that was 53 cm thick. The Geogrid, even though it was frozen into the top 7.6 cm of the ice sheet, reduced the deflection of the ice sheet.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Standard Practice for Use of the International System of Units (SI)*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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F. Donald Haynes, Charles M. Collins
and Walter W. Olson

December 1992

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by F. Donald Haynes, Mechanical Engineer, Ice Engineering Research Branch, Experimental Engineering Division, Charles M. Collins, Research Physical Scientist, Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory, and Major Walter W. Olson, U.S. Army Corps of Engineers. Funding for this work was provided by DA Project 4A762784AT42, *Cold Regions Engineering Technology;* Task CS, *Cold Regions Technology;* Work Unit E03, *Combat Engineering in Winter.*

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NOMENCLATURE

a	– radius of uniform load, m
D	– flexural rigidity, N–m
E	– Young's modulus, N/m^2
F	– force
h	– ice thickness, m
k	– specific weight of water, N/m^3
ℓ	– characteristic length, m
q	– uniform load, N/m^2
r	– radial distance, m
w, W	– vertical deflection, m
∇	– Laplacian delta
ν	– Poisson's ratio

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F. DONALD HAYNES, CHARLES M. COLLINS
AND WALTER W. OLSON

INTRODUCTION

Ice bridges and ice roads are constructed on rivers, lakes and oceans every winter in cold regions around the world. Often, this construction consists of removal of snow from the natural ice cover to allow thickening of the ice sheet by natural growth or flooding of the ice with successive thin layers of water, which freeze and thicken it from the surface. In either case, the thickening of the ice sheet increases its bearing capacity. Another method of increasing the bearing capacity is to reinforce the ice with some material frozen into the ice. Various materials have been used, including rice straw, branches, plastic rods, timbers, sawdust, fiberglass and steel cables.

Important experimental and theoretical work on floating ice sheets has been done by Wyman (1950), Assur (1956), Frankenstein (1966), Nevel (1970, 1978) and Frederking and Gold (1976). Kerr (1976) has written a comprehensive review of work done on the capacity of floating ice sheets to support static loads. Ashton (1986) has reviewed both theoretical and experimental work on the bearing capacity of ice sheets. Churchill (1951) describes how wood pulp added to sea ice was considered for making a floating structure suitable for landing aircraft in World War II. Although this "Pykrete," as it was called, never was used, it was tested and found to be very strong. Another advantage of Pykrete was that, as the ice melted, the fibrous material formed a furry outer surface that insulated the remaining ice and slowed the melting process. Kingery (1960) reports tests conducted by adding sawdust and fiberglass to sea ice. He found that, by adding 15% fiberglass by volume, the strength of sea ice was increased about 10 times. Rice straw was used to reinforce an ice bridge on the Imjin River in Korea; Carnes (1964) reports that this ice bridge was used as a crossing for M-41 tanks. DenHartog (1975) describes the use of grass, brush and logs to build ice bridges. Laboratory tests on ice reinforced with branches, steel cables and wooden dowels are reported by Ohstrom and DenHartog (1976). They conducted tests by loading cantilever beams to failure. The reinforcement was placed in the ice by first freezing it on top of the ice sheet and then flooding and freezing successive lifts on the ice until the reinforcement was at the desired depth. They found that the branches, cables and dowels increased the flexural strength as much as 5.6, 3.2 and 2.6 times, respectively, for the freshwater ice and as much as 3.9, 3.2 and 5.8 times, respectively, for the sea ice. Even though the cables had the highest tensile strength, they did not produce the highest increase in flexural strength because of bonding problems with the ice.

Tests on ice reinforced with geotechnical fabrics are reported by Jarrett and Biggar (1979). Four different fabrics were cast into ice beams that were tested in flexure in the laboratory. They found that the fabric reinforcement increased the flexural strength up to 31%. Creep tests on ice beams with small fiberglass rods frozen into them were conducted by Grabe (1986). By using four-point bending tests, he found that reinforcing the beam on the top and bottom considerably reduced the deformation and the deformation rate. Vasil'ev (1986) found that freezing fiberglass into ice increased its strength up to 10 times, depending upon the amount of fiberglass and also upon the orientation of the fibers.

Field tests on floating freshwater ice reinforced with either sand, birch branches or sawn timber were made by Fransson and Elfgren (1986). The ice was loaded by a truck (182 kN) for 20 minutes while deflection of the ice was measured. Secondary creep of the ice sheet was fully established after about 4 minutes of loading. From these data they developed a three-parameter, linear viscoelastic creep model. The reinforcement materials were placed on top of the ice and frozen-in with water flooding. They point out that the reinforcement material should be considerably stiffer than the ice so that there is a transfer of load from the ice to the reinforcing material with increasing load or creep, or both, of the ice. This explained why the ice reinforced by timbers deflected less than the ice reinforced by the more pliant branches. Fransson (1983) has also tested ice beams reinforced with cables, wood or steel bars frozen into them. The flexural strength of the beams was increased as much as six times by the reinforcement. Tests with steel bars frozen into ice beams and subjected to flexural creep loading are reported by Cederwall (1981). He found that, as the ice became cracked, the load was carried by the steel bars, which greatly increased the effective flexural strength. The beams were tested at two temperatures: –10 and –15°C. Lower effective strengths, accompanied by deterioration in the bonding between the ice and the steel bars, were observed at the lower temperature. Since the linear coefficient of thermal expansion for ice is about four times that of steel, the thermal expansion incompatibility apparently was significant.

Geogrid is a rectangular polymer mesh manufactured by Tensar Corporation. It is usually used to reinforce and stabilize steep soil banks. The advantage of using Geogrid frozen into ice is that global bonding (grid–ice interlocking) is established by the rectangular mesh geometry. The use of Geogrid in ice bridges was considered by Haynes and Kerr (1987); their preliminary tests on small, simple ice beams indicated that Geogrid increased the average flexural strength of the beams by 16%. Haynes and Martinson (1989), conducting laboratory tests on ice reinforced with Geogrid, found that Geogrid bonded well with the ice and increased its bearing capacity up to 300% for very thin ice sheets.

In the present study, we conducted laboratory tests on floating ice sheets reinforced with a Geogrid mesh. The objectives of these tests were to determine 1) the effect of the reinforcement when the ice was loaded to failure in about 15 seconds, 2) the effect of the reinforcement on the displacement of the ice, and 3) the effect of the reinforcement on the failure mode of the ice sheet. These tests were designed to more closely simulate moving rather than stationary loads. Field tests were also conducted to determine if Geogrid, frozen into an ice sheet, would affect the deflection of the ice sheet under load.

LABORATORY TESTS

The bearing capacity tests were conducted in the test basin of the Ice Engineering Facility at CRREL. The basin was divided into four sections so that three sections of each ice sheet had Geogrid-reinforced ice and one section had unreinforced ice as a control.

The freshwater ice was grown by first seeding the water surface to initiate the ice cover and then continuing the growth in low ambient temperatures to the desired depth. This method resulted in an ice sheet with a small top layer of fine-grained ice while the major portion of the ice sheet was composed of columnar-grained ice. For each ice sheet, the flexural strength was found by breaking cantilever beams. In addition, the elastic modulus and characteristic length were obtained by placing a load on the ice sheet, measuring the deflection of the load and using the plate deflection equations developed by Wyman (1950) and a method described by Kerr and Haynes (1988).

Our Geogrid had a grid size of 5 × 7.6 cm, was black, and was made from a single polymer sheet, punched and drawn at elevated temperature to the desired grid size so that the ribs were an integral part of the grid structure. The smallest cross section of an individual rib measured 1 × 4 mm.

Two methods were used to place the material in the ice sheet, both taking advantage of Geogrid's buoyancy. In the first method, the 3.66- × 9-m piece of Geogrid was held on the bottom of the basin by weights until an ice sheet was grown to a desired depth. Then the weights were removed, which allowed the Geogrid to float up to the underside of the ice. The ice was then grown to the desired thickness, encapsulating the Geogrid in the process. For the second method, we cut a 15-cm-wide slot in the ice, the full 9-m length of the Geogrid, then slid the material under the ice as shown in Figure 1. The ice was then grown to the desired thickness, also encapsulating the Geogrid. The

Figure 1. Deploying Geogrid by slipping it under an ice sheet through a slot cut in the ice.

Geogrid was frozen in about midway through the ice thickness for ice sheets 1 and 2, and at about one-quarter of the thickness from the bottom for ice sheets 3–6. In ice sheet 1, we simply floated the Geogrid on top of the water and allowed it to freeze in. Since the Geogrid was not very flat, it was above the ice at some points. For test 20 in ice sheet 6, two Geogrids were frozen into the ice, one about midway and the other about one-quarter of the thickness from the bottom.

A bearing capacity test was conducted on each ice section. A schematic of the test setup is shown in Figure 2. The load was applied via a wooden disk with a diameter of 16.5 cm. A load cell was used to measure the load and three displacement transducers were used to measure the deflection of the ice. The load was applied by lowering the center truss section of a personnel carriage that spanned the basin. Four motor-driven jacks moved the center truss section uniformly at one fixed rate—6.6

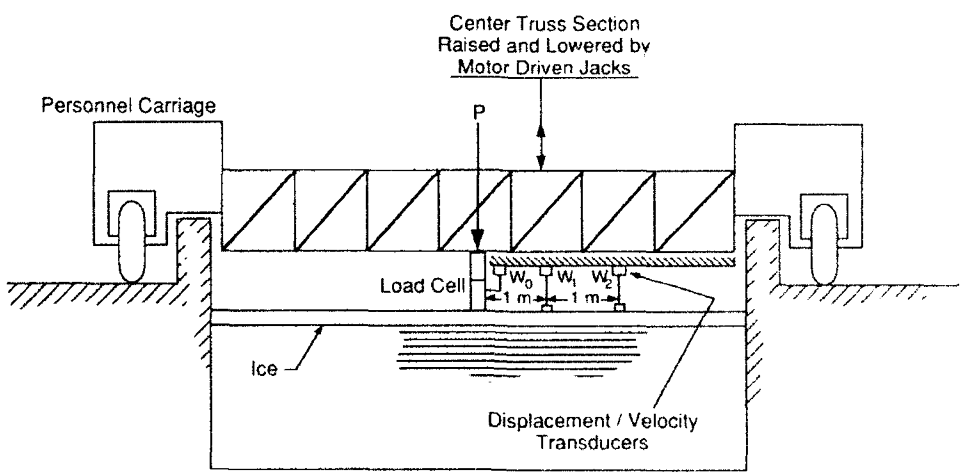


Figure 2. Schematic of the bearing capacity test. W_0, W_1 and W_2 are deflections of the ice sheet measured by the transducers at the locations shown.

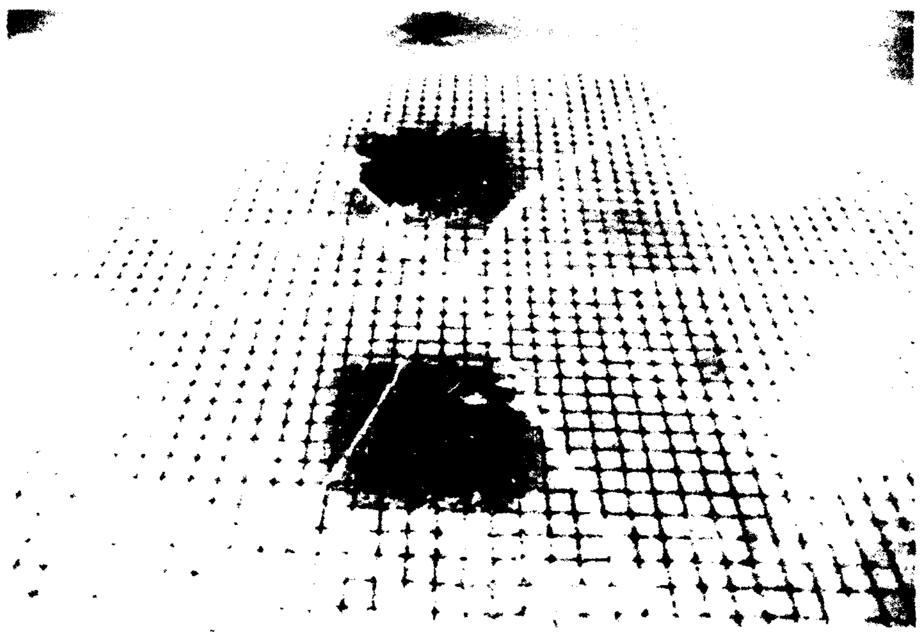


Figure 3. Geogrid frozen into the ice sheet with radial cracks formed by an applied load.

mm/s. Figure 3 is a photograph of a Geogrid section after a test. All data were collected by a computer controlling a high-speed data logger.

TEST RESULTS

A total of 22 tests were made on six different ice sheets. The results are summarized in Table 1. In ice sheets 4, 5 and 6, the elastic modulus E was found for a section of ice with Geogrid and for a section of ice without Geogrid. We found that Geogrid frozen into the ice increased the modulus up to 48% (i.e., it increased the characteristic length ℓ up to 10%). In tests 1 and 5 (without Geogrid), the ice sheet was loaded to catastrophic, or rapid and complete, failure after radial and circumferential cracks had formed. In tests with the Geogrid (2, 3, 4 and 6), the ice sheet was loaded until the maximum travel of the loading device was reached without breakthrough. At this time the ice was flooded and had radial and circumferential cracks, but there was no catastrophic ice failure.

The maximum force in test 4 (with Geogrid) was about three times that in test 1 (without Geogrid). This illustrates how Geogrid can provide a safety net even though the ice is cracked and flooded. It also indicates that, on very thin ice (h = 30 mm), Geogrid greatly increases bearing capacity by carrying the load itself. The maximum force in test 6 (with Geogrid) is 38% higher than that in test 5 (without Geogrid). In test 7 (without Geogrid), ice sheet 3, with thicker ice, experienced a punch-through failure with a rapid and total drop in the force (Fig. 4a). The ice with the Geogrid (tests 8, 9 and 10) failed by being potholed (Fig. 4b), where the Geogrid was not broken but the ice broke away from it in pieces directly under the load, leaving the holes. The maximum force in test 8 is 13.4% higher than that in test 7. Figure 4b also shows that the ice sheet had significant strength after the failure because the failure was local and the remainder of the ice sheet was intact.

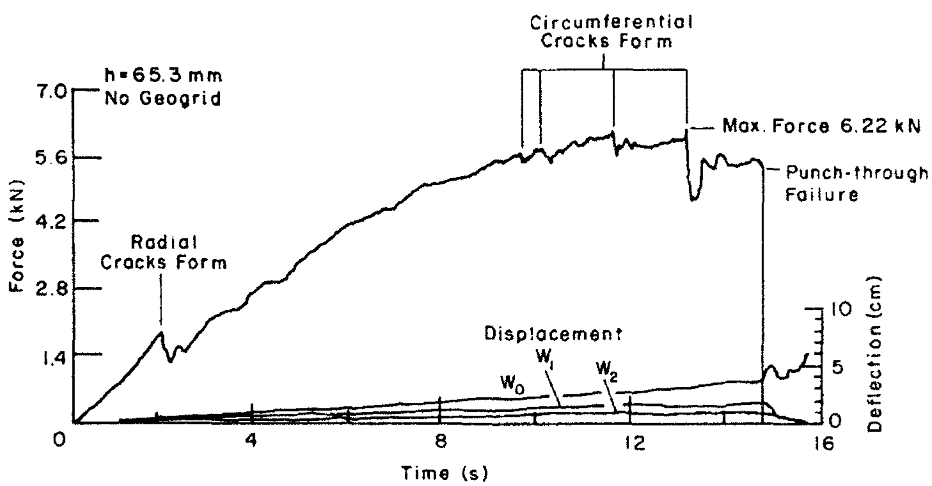
Since the test basin is only 9.1 m wide, we observed some effects from the basin walls in tests on ice sheet 4, which was 96.6 mm thick. The ice failed catastrophically in test 11 (without Geogrid), as shown in Figure 4c. For test 12 (with Geogrid), the ice and Geogrid failed by shear in a punch-through manner (Fig. 4d). A photograph of test 12 (Fig. 5) shows that there were radial cracks, but no circumferential cracks and no flooding. The shear failure was very local, analogous to a bullet penetrating a windshield but leaving the windshield intact. Tests 13 and 14 were stopped well before the ice failed so as not to destroy the loading device. The maximum force in test 14 (with Geogrid) was 64% larger than that for test 11 (without Geogrid).

The 134.9-mm-thick ice failed catastrophically in test 15 (without Geogrid). All remaining tests—

Table 1. Bearing capacity tests.

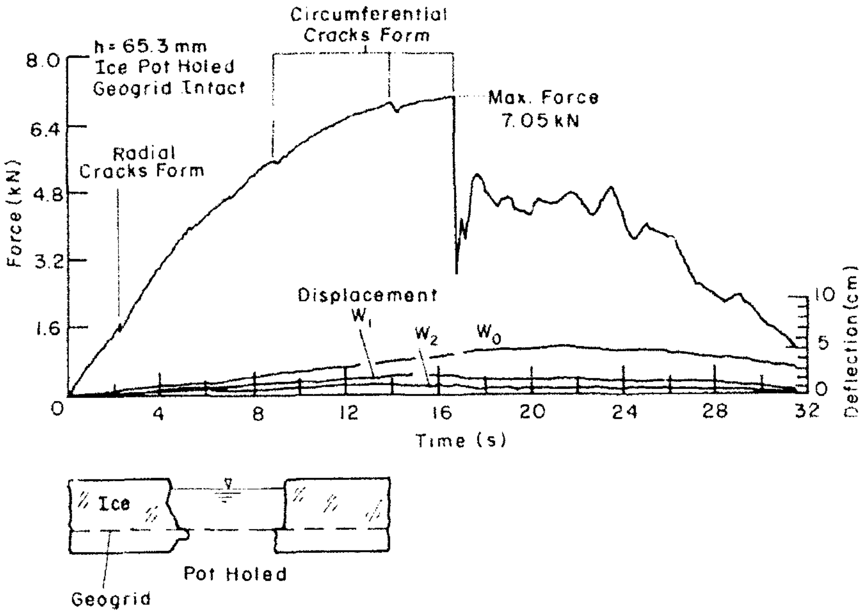
Test no.	h (mm)	ℓ (m)	E (GPa)	F_{radial} cracks formed (N)	F_{max} (N)	Remarks
				Ice sheet 1		
1*	30	0.85*	2.1*	475	1520	Geogrid not completely
2	30			390	1615	frozen into the ice.
3	30			377	1340	
4	30			341	4548	
				Ice sheet 2		
5*	49	1.29*	2.5*	1128	3978	
6	49			3510	5491	
				Ice sheet 3		
7*	65.3	1.76*	3.7*	1852	6222	
8	65.3			1681	7055	Potholed, Geogrid intact.
9	65.3			1291	7017	Potholed, Geogrid intact.
10	65.3			1633	6519	Potholed, Geogrid intact.
				Ice sheet 4		
11*	96.6	2.72*	6.5*	2281	13,854	
12	96.6	2.74	6.7	3352	15,239	Shear plug, Geogrid sheared.
13	96.6	2.74		1796	11,607	Test stopped before failure.
14	96.6	2.74		—	22,708	Test stopped before failure.
				Ice sheet 5		
15*	134.9	3.74*	8.6*	4478	23,123	
16	134.9	4.13	12.7	—	16,566	Test stopped before failure.
17	134.9	4.13		—	16,245	Test stopped before failure.
18	134.9	4.13		—	16,465	Test stopped before failure.
				Ice sheet 6		
19*	108.8	3.25*	9.2*	3746	15,183	Test stopped.
20	108.0	3.56	13.3	3499	15,631	Two Geogrids frozen-in, test stopped.
21	108.0	3.56		3792	15,477	Floated under, test stopped.
22	108.0	3.56		3004	14,403	Not frozen-in well, test stopped.

* No Geogrid.

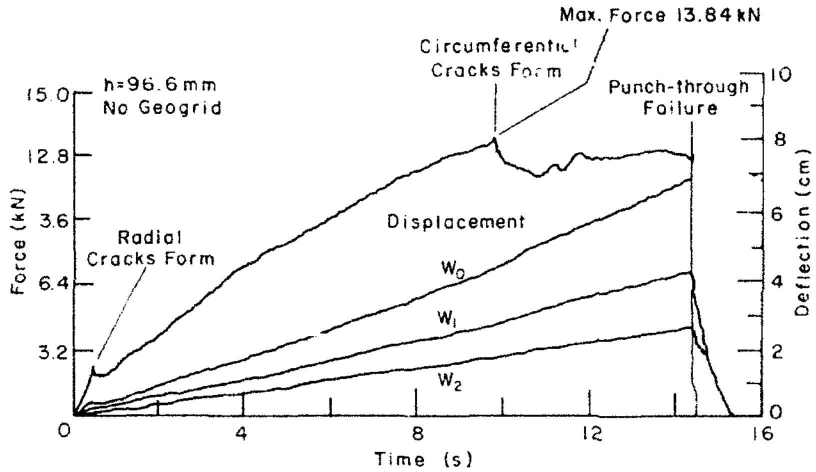


a. Test 7 without Geogrid.

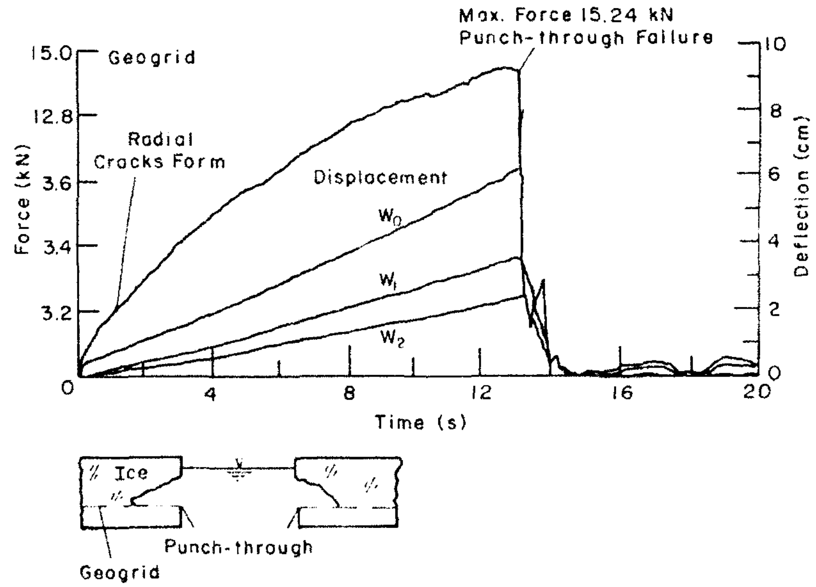
Figure 4. Plots of force and displacement vs time.



b. Test 8 with Geogrid.



c. Test 11 without Geogrid.



d. Test 12 with Geogrid.

Figure 4 (cont'd). Plots of force and displacement vs time.

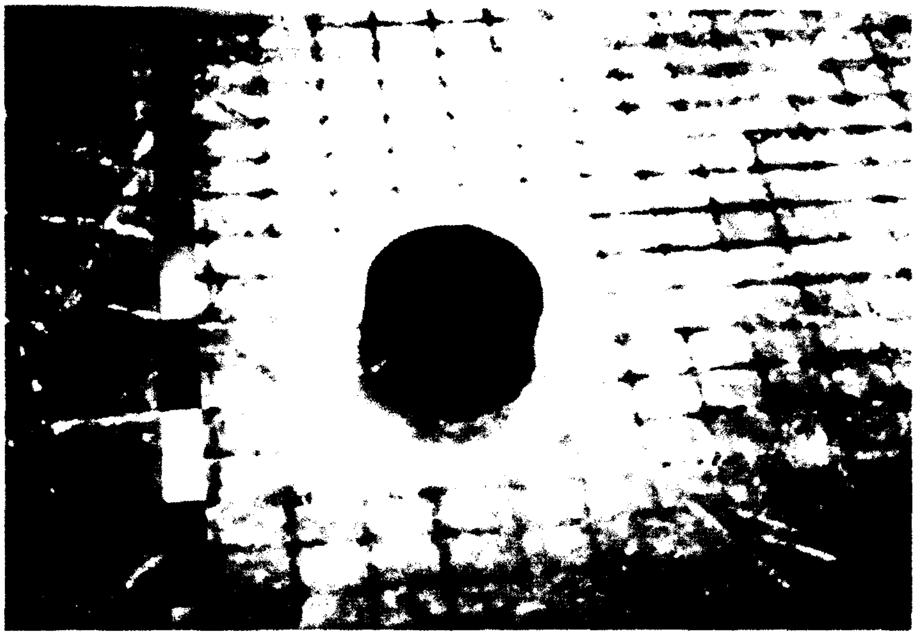


Figure 5. Test 12—the wooden disk sheared through the ice and the Geogrid.

16 through 22—were stopped to avoid damaging the loading device. In test 20 two Geogrids were frozen into the ice sheet at depths of about one-third and two-thirds of the ice thickness. The ultimate strength for this configuration was not found because of the capacity of the loading device.

FIELD TESTS

Field tests were conducted in Alaska during 1989. These tests were made on ice that had frozen on a gravel pit located on Fort Wainwright (Fig. 6). The gravel pit is essentially a small lake about 500 × 400 m and about 5 m deep.

The tests was conducted on 12 January 1989. The 47th Engineering Company, 6th Engineering Battalion, had deployed a roll of Geogrid in October 1988. A roll of Geogrid covers an area of 3.66 × 50.3 m and weighs 43 kg. The mesh size of this Geogrid was 5 × 7.6 cm also. It was deployed by cutting an opening the size of a roll of the material in a 7.6-cm-thick ice sheet and floating the Geogrid on the water. The area was later flooded two times in an attempt to position the Geogrid in the resulting ice sheet towards its bottom half, the optimum position for reinforcement being near the bottom quarter of the sheet. In this position, tensile stresses in a vertically loaded ice sheet can be transferred to

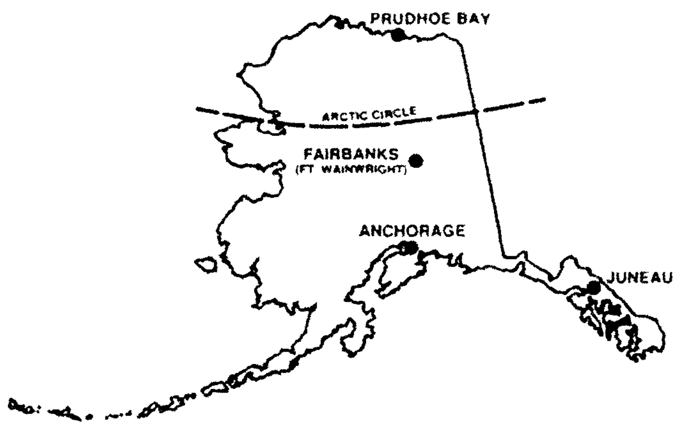


Figure 6. Alaska and the location of Fort Wainwright.

the Geogrid, allowing it to reinforce the ice sheet. We found that the Geogrid was only 7.6 cm from the top of the sheet, which was 53 cm thick on the day of testing. The ice sheet also had 46 cm of snow on it.

The ice sheet was loaded by driving a Small Unit Support Vehicle (SUSV, M-937A1), shown in Figure 7, onto the ice. The SUSV weighed 4364 kg. Two areas on the ice sheet, about 60 m apart, were staked out, one with the Geogrid and one without Geogrid. After the SUSV was driven into position, deflection of the ice sheet was measured with a level set up on shore and a level rod placed on the ice next to the

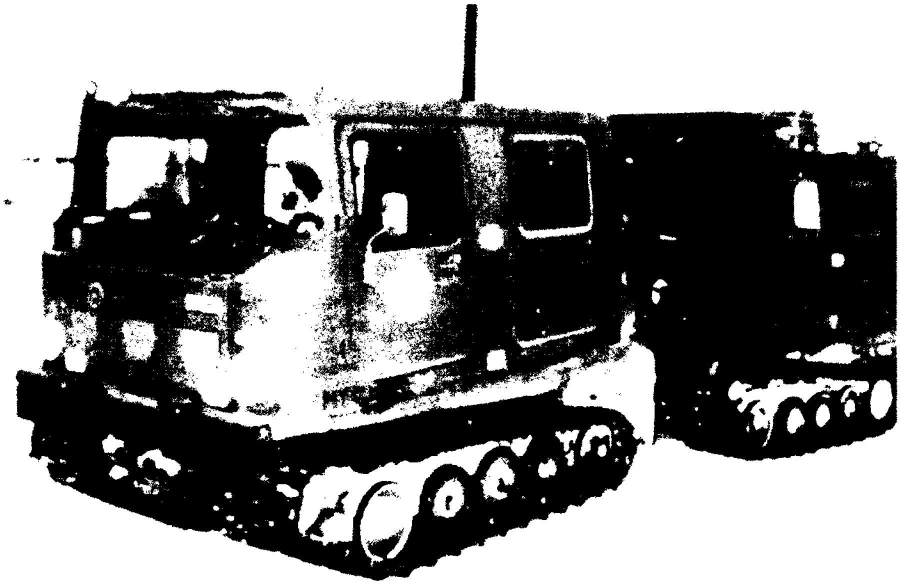


Figure 7. SUSV (Small Unit Support Vehicle).

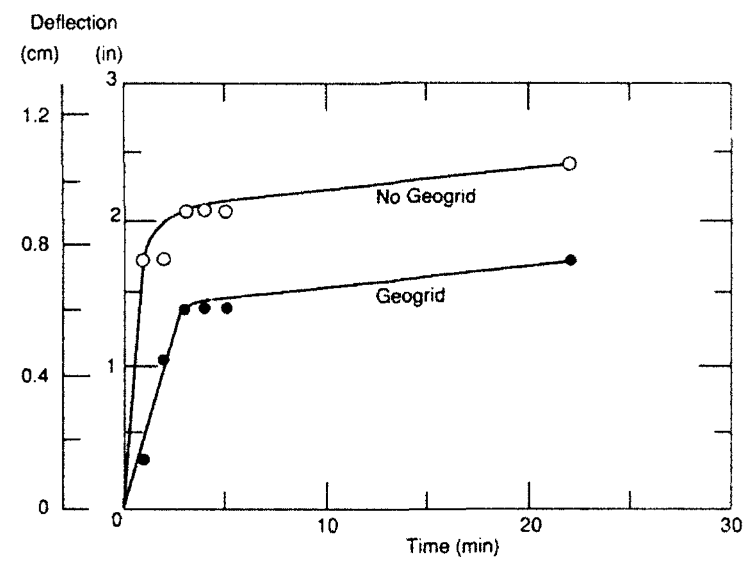


Figure 8. Ice deflection vs time for the field test with the SUSV.

vehicle. The level rod was read every minute for the first 5 minutes and then at 24 minutes.

Ice deflection results are shown in Figure 8. The ice without the Geogrid deflected about 40% more than the ice with the Geogrid, illustrating the reinforcing effect of the Geogrid. In addition, secondary creep was achieved in about 5 minutes for both the areas. This is similar to results reported by Fransson (1983).

DISCUSSION

Elastic theory can be used to analyze the dynamic laboratory tests because time to failure was about 15 seconds, which is well before creep effects become significant. Deflections of the ice with and without Geogrid are compared to determine the ability of Geogrid to stiffen the ice sheet and produce the local failure observed. The differential

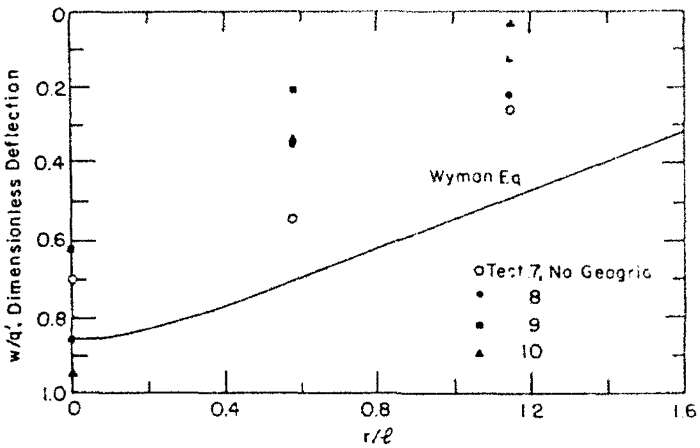


Figure 9. Deflection of the ice sheet as a function of distance from the point of load application for laboratory tests 7–10.

equation for the deflection of an infinite, homogeneous elastic plate on an elastic foundation is

$$D\nabla^4 w + kw = q \tag{1}$$

where w = deflection
q = distributed load applied over a circular area of radius a
k = specific weight of water
D = $Eh^3/[12(1-\nu^2)]$, flexural rigidity of the plate
h = ice thickness
E = Young's modulus
ν = Poisson's ratio.

It should be noted that the Geogrid mat, with its rectangular grid pattern, introduces an orthotropy when it is frozen into an ice sheet that is not represented in eq 1.

Wyman (1950) found solutions for the deflection of a floating sheet as a function of r, the distance from the center of the load, to be

$$w = q\left(1 + \frac{a}{\ell}\,\mathrm{ker}'\left(\frac{a}{\ell}\right)\right)/k \tag{2}$$

for $r = 0$

$$w = \frac{q}{k}\left[1 + \frac{a}{\ell}\left(\mathrm{ker}'\,\frac{a}{\ell}\;\mathrm{ber}\,\frac{r}{\ell} - \mathrm{kei}'\,\frac{a}{\ell}\;\mathrm{bei}\,\frac{r}{\ell}\right)\right] \tag{3}$$

for $r \le a$, and

$$w = \frac{q}{k}\,\frac{a}{\ell}\left(\mathrm{ber}'\,\frac{a}{\ell}\;\mathrm{ker}\,\frac{r}{\ell}\;\mathrm{bei}'\,\frac{a}{\ell}\;\mathrm{kei}\,\frac{r}{\ell}\right) \tag{4}$$

For $r \ge a$, where ber, bei, ker and kei are modified Bessel functions and $\ell = (D/k)^{1/4}$ is the characteristic length

A comparison of Wyman's solutions to the measured deflections at the instant of radial crack formation for laboratory tests 7–10 is shown in Figure 9. The dimensionless deflection w/q' is plotted as a function of dimensionless radial distance r/ℓ. Here w is the deflection, and $q' = q/k$, where q is the applied load divided by the loading area and k is the specific weight of water. The measured deflections under the load show some agreement with Wyman's solution. However, away from the load at $r/\ell = 0.58$ and 1.15, the measured deflections are all less than Wyman's solution. This discrepancy may be partially explained by Wyman's assumption of an infinite ice sheet, while the ice tested had boundaries that may have affected the deflection. In fact, it appears that the test basin walls can have an effect on tests involving ice bending when the ice thickness is greater than 65 mm. Tests with thicker ice are needed, but these will have to be made in a larger tank or in the field. For the ice sheets with the Geogrid (tests 8–10), the deflection at $r/\ell = 0.58$ and 1.16 are all less than the deflection of the ice sheet without the Geogrid (test 7). This illustrates the effect of the Geogrid: it tends to stiffen the ice and localize ice damage. As found in tests 8 and 12, the punch-through failure was local, leaving the remainder of the ice sheet with radial cracks but still capable of carrying a substantial load.

The present dynamic tests on floating ice sheets indicate that Geogrid increases the maximum bearing capacity up to 300% for very thin (30 mm) ice, up to 38% for thin (49 mm) ice and about 10–15% for thicker (65 mm) ice. As the ice becomes cracked, the load is carried by the Geogrid (a long, continuous mat), which increases the bearing capacity. With thicker ice, the percentage of Geogrid reinforcement by volume is lower than with thinner ice and the increase in bearing capacity is also lower. Of course, the volume of Geogrid can be increased by using several layers in an ice sheet. However, only when tests are made on larger ice sheets without the effect of the nearby walls will the increase in bearing capacity be fully known for ice thicker than 65 mm.

The field test in January 1989 using the SUSV to load the ice demonstrated the challenge of positioning the Geogrid in the ice sheet. Although an attempt was made to position the Geogrid in the lower quarter of the ice sheet via flooding, it ended up being only 7.6 cm from the top. Another attempt was made to position a second roll of Geogrid towards the bottom of the ice sheet by using the laboratory method of cutting a slot in the ice, big enough to slip the Geogrid through, and letting the ice grow through it. This was done for the SUSV test site, but two problems were encountered. First, it was difficult to shove the full length of Geogrid under the ice because it unrolls in an undulating shape and does not lay flat up against the underside of the ice sheet. Second, snow accumulated on the ice sheet and retarded the ice growth. Drilling some holes through the ice sheet prior to the test showed us that the Geogrid was not frozen into the ice, but was simply floating against the bottom of the ice sheet.

There is a need to develop a technique for deploying Geogrid under field conditions because what is relatively simple to do in the laboratory becomes a challenge in the field. If the approach of flooding is taken, it appears that the ice should be flooded systematically, possibly every 6–10 hours, until the desired thickness is reached. If the approach of slipping the Geogrid under the ice is taken, several methods could be tried. One is to cut a slot the length (50.3 m) of the Geogrid and then slip it in sideways. Another method may be to remove the ice and keep the Geogrid submerged with weights, and then let the ice grow through it. It is important, however, to keep snow off the surface of the ice so that the ice can grow through the Geogrid.

It is evident from Figure 8 that the Geogrid did reinforce the ice that was loaded by the SUSV. This was achieved with the Geogrid being 7.6 cm from the top of the 53-cm-thick ice sheet. After 1 minute,

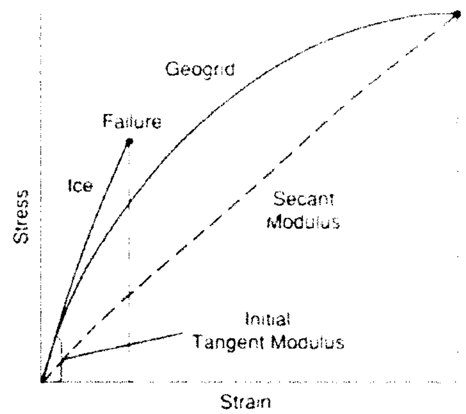


Figure 10. Sketch showing the initial tangent modulus and secant modulus for ice and Geogrid in uniaxial tension tests.

the ice with Geogrid deflected only 20% as much as the ice without Geogrid. After 22 minutes, the ice with the Geogrid had deflected 70% as much as the ice without Geogrid. If the Geogrid had been positioned towards the bottom of the ice sheet, its reinforcing effect might have been greater.

Another result that Figure 8 shows is that the initial deflection, during the first 3 minutes, is greater for the ice without Geogrid, which is similar to the results of the short-term (15-second) laboratory tests in which Geogrid stiffens the ice. However, the deflections from 5 to 22 minutes are about the same for the ice with and without Geogrid.

Some uniaxial tension tests were conducted on Geogrid alone in the laboratory. We found that Geogrid experienced considerable strain (stretching) before it failed in rupture. This is illustrated in Figure 10. The results in Figure 8 may be explained by the observation that the initial tangent modulus for ice and Geogrid are about the same, which lets the Geogrid carry some of the stresses in the ice sheet and stiffen it. However, the secant tangent modulus for Geogrid is less than that for ice and, therefore, the deflections during the secondary creep phase are about the same for ice with and without Geogrid. In summary, we can say that, in the primary creep phase, the Geogrid may carry more of the stresses than it does in the secondary creep phase.

Increasing the bearing capacity of intact ice is only one of the advantages of using Geogrid; another advantage is the localized failure of the ice with Geogrid and the load-carrying capability of the ice after failure. Other advantages in using Geogrid over other materials are its relatively low cost (about $500 for a roll that covers an area of 3.4

× 50 m), light weight (a roll weighs only 43 kg), relative ease of deployment, and potential for recovery and reuse. Another advantage of Geogrid is that it appears to have excellent bonding characteristics with ice. The greatest potential application for Geogrid for ice bridging may be in climatic areas that are marginal for growing ice and for relatively lightweight loads. It may have potential use on ice roads in critical areas that have thin or highly cracked ice.

There may be many other applications in cold regions where Geogrid could be advantageously used. The use of geotechnical fabrics on ice-capped snow roads was suggested by Jarrett and Biggar (1986). Perham* considered the use of Geogrid to hold river ice in place. This could be done by freezing part of the roll into the ice sheet and anchoring the remainder on shore. One application here is to prevent ice from breaking away from shore and clogging ship channels. Future plans include creep tests, multiple point loading tests and field tests.

CONCLUSIONS

The bearing capacity tests conducted in CRREL's test basin on floating ice sheets with and without Geogrid reinforcement produced the following results.

For the ice sheets tested, Geogrid increased the maximum load-carrying capability of 30-mm ice up to 300%, of 49-mm ice up to 38%, of 65 mm ice up to 13% and of 96-mm ice from 10 to 15%. However, there may have been some effect of the nearby walls on the 96-mm ice sheet.

Failure of ice with Geogrid is quite different from failure without Geogrid, i.e., failure without Geogrid was over a large area while failure with Geogrid was highly localized.

Away from the load, ice reinforced with Geogrid deflected less than that without Geogrid. This illustrated a tendency of the Geogrid to stiffen the ice in dynamic tests.

Field tests were conducted at Fort Wainwright, Alaska. In these tests a SUSV was used for loading a 53-cm-thick ice sheet. The Geogrid, even though it was frozen into the top 7.6 cm of the ice sheet, reduced the deflection of the ice sheet.

The advantages of using Geogrid for reinforcement include low cost, light weight, ease of deployment, good bonding characteristics with ice and possible reusability. One disadvantage is its black color and potential for absorbing solar energy, which may result in melting and debonding with the ice. However, white Geogrid can be obtained at an increased cost.

*Personal communication with R. Perham, CRREL, 1987.

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Laboratory tests were conducted on floating freshwater ice sheets, reinforced with a high-strength polymeric mesh (Geogrid). The mesh was frozen into the ice sheets. Bearing capacity tests were conducted on each ice sheet, whose thickness varied from 3 to 13 cm, while the dynamic loads varied from 1.3 to 23 kN. Comparisons to tests on ice without reinforcement were made; Geogrid reinforcement increased the bearing capacity of thin (49-mm) ice up to 38% and of thicker ice (96 mm) about 10–15%. Failure of the ice with Geogrid reinforcement was local, whereas failure of the ice without Geogrid was over a large area. Displacement of the ice is compared to theory for plates on an elastic foundation. Field tests were conducted at Fort Wainwright, Alaska. A small unit support vehicle (Hagglunds BV 206) was used for loading a reinforced ice sheet that was 53 cm thick. The Geogrid, even though it was frozen into the top 7.6 cm of the ice sheet, reduced the deflection of the ice sheet.

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